$$+ \quad \sum_{n,q} \text{COALLOWSUL}_{n,q} \cdot \mathit{lowsuladd\_LCF}_n \cdot \mathit{CHeatRate}_q$$

[surcharge for using low sulfur coal]

$$+ \quad \text{RPS\_shortfall} \cdot \mathit{RPSSCost}$$

$$+ \quad \sum_{states} \text{St\_RPSshortfall}_{states} \cdot \mathit{St\_RPSSCost}$$

$$+ \quad \sum_{states} \text{St\_CSPRPSshortfall}_{states} \cdot \mathit{St\_CSPRPSCost}_{states}$$

[costs of shortfalls in failing to meet RPS requirements]

A.4 Constraints

The minimization of cost in ReEDS is subject to a large number of different constraints, involving limits on resources, transmission constraints, national growth constraints, ancillary services, and pollution. Unless specifically noted otherwise (see, for example, the wind resource limit below), these constraints apply to new generating capacity built in the time period being optimized.

The constraint name is shown with the subscripts over which the constraint applies. For example, in the constraint immediately below, the subscript 'c, i, l' immediately following the name of the constraint implies that this constraint is applied for every class of wind c, every region i, and every location l. Because there are 356 regions, five classes of wind, and 3 locations, this first type of constraint is repeated 5,340 times (356x5x3).

A.4.1 Constraints on Wind

Wind Resource Constraint: For every wind class c and wind supply region i, the sum of all wind capacity installed in this and preceding time periods must be less than the total wind resource in the region.

$\mathit{WIND\_RES\_UC}_{c,i,l}$

$$\text{WturN}_{c,i,l} + \text{WturTN}_{c,i,l} + \text{Wtur\_inregion}_{c,i,l} \quad \leq \quad \max(0, \mathit{WRuc}_{c,i,l} - \mathit{WturO}_{c,i,l} - \mathit{WTturO}_{c,i,l})$$

Wind Supply Curve: New wind of class c in region i at interconnection cost step $wscp$ must be less than the remaining wind resource in that cost step.[10] The second constraint balances the wind on pre-2006 lines across the different supply curve points and is used to determine the cost of transmission required to reach the grid.

$\mathit{WIND\_supply\_curves}_{c,i,l,wscp}$

$$\text{WturN}_{c,i,l,wscp} \quad \leq \quad \max(0, \mathit{WR2G}_{c,i,l,wscp})$$

$\mathit{WIND\_EXISTRANS\_BALANCE}_{i,l}$

$$\sum_{wscp} \text{WNSC}_{i,l,wscp} \quad = \quad \sum_{j} \text{WN}_{i,j,l}$$

[10] A preliminary optimization is performed outside and prior to the main model to construct a supply curve for onshore wind, shallow offshore wind, and deep offshore wind for each wind class c and region i. This supply curve is comprised of four quantity/cost pairs ($\mathit{WR2G}_{c,i,l,wscp}$ / $\mathit{WR2GPTS}_{c,i,l,wscp}$). The "curve" provides the amount of class c wind $\mathit{WR2G}_{c,i,l,wscp}$ that can be connected to the pre-2006 grid for a cost between $\mathit{WR2GPTS}_{c,i,l,wscp-1}$ and $\mathit{WR2GPTS}_{c,i,l,wscp}$. This "pre-LP" optimization is described in more detail in Appendix G. The quantity $\mathit{WR2G}_{c,i,l,wscp}$ is reduced after each period's LP optimization by the amount of wind used in the time period from that cost step.

Wind Transmission Constraint: The new class c wind transmitted from a region i to all regions j must be less than or equal to the total amount of new region i class c wind used from the class c wind supply curve.

$WIND\_2\_GRID_{c,i,l}$

$$\sum_j \mathrm{WN}_{c,i,j,l} \leq \sum_{wscp} \mathrm{WturN}_{c,i,l,wscp}$$

$WIND\_2\_NEW_{c,i,l}$

$$\sum_j \mathrm{WTN}_{c,i,j,l} \leq \sum_{wscp} \mathrm{WturTN}_{c,i,l,wscp}$$

$WIND\_INREGION_{c,i,l}$

$$\sum_{escp} \mathrm{Welec\_inregion}_{c,i,l,escp} \leq \mathrm{Wtur\_inregion}_{c,i,l}$$

Wind Growth Constraint: These two constraints allocate new wind capacity (MW) to bins that have turbine prices that are higher than the costs during periods of rapidly growing demand. The bins are defined as a fraction of the national wind capacity (MW) at the start of the period.

$WIND\_GROWTH\_TOT$

$$\sum_{c,i,l} (\mathrm{WturN}_{c,i,l} + \mathrm{WturTN}_{c,i,l} + \mathrm{Wtur\_inregion}_{c,i,l}) \leq \sum_g \mathrm{WCt}_g$$

$WIND\_GROWTH\_BIN_g$

$$\mathrm{WCt}_g \leq Gt_g \cdot BASE\_WIND$$

Wind Installation Growth Constraint: These two constraints allocate new wind capacity (MW) to bins that have installation costs associated with them over and above the base costs of installation. The bins are defined as a fraction of the regional wind capacity (MW) at the start of the period.

$WIND\_GROWTH\_INST_i$

$$\sum_{c,l} (\mathrm{WturN}_{c,i,l} + \mathrm{WturTN}_{c,i,l} + \mathrm{Wtur\_inregion}_{c,i,l}) - 200 \leq \sum_{ginst} \mathrm{WCtinst}_{i,ginst}$$

$WIND\_GROWTH\_BIN\_INST_{i,ginst}$

$$\mathrm{WCtinst}_{i,ginst} \leq Gtinst_{ginst} \cdot BASE\_WIND\_inst_i$$

Wind Curtailments: This constraint defines wind curtailments to be the maximum of zero and the difference between the wind-generated electricity consumed in region j in time-slice m and all the electricity consumed in region j (i.e., $\mathrm{WS}_{n,m}$ is non-zero only if the wind power consumed in balancing area n is greater than the total demand in time-slice m. This can occur in off-peak time-slices if large amounts of wind are sent to n to meet the demand in other time-slices). $\mathrm{WS}_{n,m}$ is then subtracted from the wind contribution to meeting the *LOAD_PCA* constraint for time-slice m. In effect, these two constraints impose a penalty on excessive shipments of wind to an individual region j by not counting the wind power that exceeds the demand in any individual time-slice. This precludes the model from shipping wind to a region near the wind production region and then shipping the wind generation out with conventional generation to other balancing authorities using conventional lines, i.e. without taking account of the fact that any transmission reserved for wind will only be used when the wind is blowing.

$WIND\_DEMAND\_LIMIT_{n,m}$

$$
\begin{aligned}
\mathrm{WS}_{n,m} \quad \geq \quad & \sum_{c,i,j,l}^{j \in n} (\mathrm{WN}_{c,i,j,l} + \mathrm{WTN}_{c,i,j,l} + \mathrm{Welec\_inregion}_{c,j,l}) \cdot (1 - \mathit{TWLOSSnew} \cdot \mathit{Distance}_{i,j}) \\
+ \quad & \sum_{c,i,j,l}^{j \in n} (\mathit{WO}_{c,i,j,l} + \mathit{WTO}_{c,i,j,l}) \cdot (1 - \mathit{TWLOSSold} \cdot \mathit{Distance}_{i,j}) \\
- \quad & \sum_{st} \mathrm{STORin}_{n,m,st} \\
- \quad & \sum_{j,st}^{j \in n} \mathrm{WSTORin\_grid}_{j,m,st} + \mathit{old\_WSTORin\_grid}_{j,m,st} \\
- \quad & \sum_{j}^{j \in n} L_{j,m}
\end{aligned}
$$

A.4.2 Constraints on CSP

CSP Resource Limit: For every CSP class and supply region i, the sum of all CSP capacity installed in this and preceding time periods must be less than the total solar resource in the region.

$CSP\_REC\_UC_{cCSP,i}$

$$
\begin{aligned}
& \mathrm{CSPturN}_{cCSP,i} + \mathrm{CSPturTN}_{cCSP,i} \quad + \\
& \qquad \mathrm{CSPtur\_inregion}_{cCSP,i} \quad \leq \quad \max(0, \mathit{CSPRuc}_{cCSP,i} - \mathit{CSPturO}_{cCSP,i} - \mathit{CSPTturO}_{cCSP,i})
\end{aligned}
$$

CSP Supply Curve: New CSP of class cCSP in region i at interconnection cost step *cspscp* must be less than the remaining solar resource in that cost step. The second constraint balances the CSP on pre-2006 lines across the different supply curve points and is used to determine the cost of transmission required to reach the grid.

$CSP\_supply\_curves_{cCSP,i,cspscp}$

$$
\mathrm{CSPturN}_{cCSP,i,cspscp} \quad \leq \quad \max(0, \mathit{CSP2G}_{cCSP,i,cspscp})
$$

$CSP\_EXISTRANS\_BALANCE_i$

$$
\sum_{cspscp} \mathrm{CspNSC}_{i,cspscp} \quad = \quad \sum_{j} \mathrm{CspN}_{i,j}
$$

CSP Transmission Constraints: New CSP transmitted from a region i to all regions j must be less than or equal to the total amount of new region i CSP used from the solar supply curve.

CSP_2_GRID$_{cCSP,i}$

$$\sum_{j} \mathrm{CSPN}_{cCSP,i,j} \leq \sum_{cspscp} \mathrm{CSPturN}_{cCSP,i,cspscp}$$

CSP_2_NEW$_{cCSP,i}$

$$\sum_{j} \mathrm{CSPTN}_{cCSP,i,j} \leq \sum_{cspscp} \mathrm{CSPturTN}_{cCSP,i,cspscp}$$

ELEC_inregioncsp$_{cCSP,i}$

$$\sum_{escp} \mathrm{CSPELEC\_inregion}_{cCSP,i,escp} \leq \mathrm{CSPtur\_inregion}_{cCSP,i}$$

CSP Growth Constraint: These two constraints allocate new CSP capacity (MW) to bins that have plant costs associated with them over and above the costs of the solar plants themselves. The bins are defined as a fraction of the national CSP capacity (MW) at the start of the period.

CSP_GROWTH_TOT

$$\sum_{cCSP,i} (\mathrm{CSPturN}_{cCSP,i} + \mathrm{CSPturTN}_{cCSP,i} + \mathrm{CSPtur\_inregion}_{cCSP,i}) \leq \sum_{gCSP} \mathrm{CSPCt}_{gCSP}$$

CSP_GROWTH_BIN$_{gCSP}$

$$\mathrm{CSPCt}_{gCSP} \leq GtCSP_{gCSP} \cdot BASE\_CSP$$

CSP Installation Growth Constraint: These two constraints allocate new CSP capacity (MW) to bins that have installation costs associated with them over and above the base costs of installation. The bins are defined as a fraction of the regional CSP capacity (MW) at the start of the period.

CSP_GROWTH_INST$_{i}$

$$\sum_{cCSP} (\mathrm{CSPturN}_{cCSP,i} + \mathrm{CSPturTN}_{cCSP,i} + \mathrm{CSPtur\_inregion}_{cCSP,i}) - 200 \leq \sum_{gCSPinst} \mathrm{CSPCtinst}_{i,gCSPinst}$$

CSP_GROWTH_BIN_INST$_{i,gCSPinst}$

$$\mathrm{CSPCtinst}_{i,gCSPinst} \leq GtCSPinst_{gCSPinst} \cdot BASE\_CSP\_inst_{i}$$

CSP Curtailments:

CSP_DEMAND_LIMIT$_{n,m}$

$$\begin{aligned}
\mathrm{CSPS}_{n,m} \geq\; & \sum_{cCSP,i,j}^{j \in n} (\mathrm{CSPN}_{cCSP,i,j} + \mathrm{CSPTN}_{cCSP,i,j} + \mathrm{CSPelec_inregion}_{cCSP,j}) \\
& \quad \cdot CF_{cCSP,m} \cdot (1 - CspSurplusMar_{cCSP,i}) \cdot (1 - TWLOSSnew \cdot Distance_{i,j}) \\
+ & \sum_{cCSP,i,j}^{j \in n} (CSPO_{cCSP,i,j} + CSPTO_{cCSP,i,j}) \\
& \quad \cdot CFO_{cCSP,m} \cdot (1 - CspSurplusOld_{i}) \cdot (1 - TWLOSSold \cdot Distance_{i,j}) \\
- & \sum_{j}^{j \in n} L_{j,m}
\end{aligned}$$

A.4.3 General Renewable Constraints

RPS Requirement: This allows the model to include a national Renewable Portfolio Standard (RPS), wherein the total national annual renewable generation must exceed a specified fraction of the national electricity load or a penalty must be paid on the shortfall.

RPSConstraint

$$
\begin{aligned}
RPSfraction \cdot \sum_{n,m} L_{n,m} \cdot H_m \quad \leq \quad & \sum_{c,i,j,m,l} (\mathrm{WN}_{c,i,j,l} + \mathrm{WTN}_{c,i,j,l}) \cdot CF_{c,i,m,l} \cdot H_m \\
& \qquad \cdot (1 - TWLOSSnew \cdot Distance_{i,j})(1 - SurplusMar_{c,j}) \\
+ \quad & \sum_{c,i,j,m,l} (WO_{c,i,j,l} + WTO_{c,i,j,l}) \cdot CF_{c,i,m,l} \cdot H_m \\
& \qquad \cdot (1 - TWLOSSold \cdot Distance_{i,j})(1 - SurplusOld_{c,j}) \\
+ \quad & \sum_{c,j,m,l} \mathrm{Welec\_inregion}_{c,j,l} \cdot CF_{c,j,m,l} \cdot H_m \\
& \qquad \cdot (1 - SurplusMar_{c,j}) \\
+ \quad & \sum_{cCSP,i,j,m} (\mathrm{CSPN}_{cCSP,i,j} + \mathrm{CSPTN}_{cCSP,i,j}) \cdot CF_{cCSP,m} \cdot H_m \\
& \qquad \cdot (1 - TWLOSSnew \cdot Distance_{i,j}) \\
+ \quad & \sum_{cCSP,i,j,m} (CSPO_{cCSP,i,j} + CSPTO_{cCSP,i,j}) \cdot CF_{cCSP,m} \cdot H_m \\
& \qquad \cdot (1 - TWLOSSold \cdot Distance_{i,j}) \\
+ \quad & \sum_{cCSP,j,m} \mathrm{CSPelec\_inregion}_{cCSP,j} \cdot CF_{cCSP,m} \cdot H_m \\
+ \quad & \sum_{c,i,m,st} (\mathrm{WSTORin\_wind}_{c,i,m,st} + old\_WSTORin\_wind_{c,i,m,st}) \cdot H_m \\
+ \quad & \sum_{n,m} (\mathrm{CONV}_{n,m,geothermal} + \mathrm{CONVP}_{n,m,geothermal}) \cdot H_m \\
+ \quad & \sum_{n,m} (\mathrm{CONV}_{n,m,biopower} + \mathrm{CONVP}_{n,m,biopower}) \cdot H_m \\
+ \quad & \sum_{bioclass,n} \mathrm{CofireGen}_{bioclass,n} \\
- \quad & \sum_{n,m} \mathrm{WS}_{n,m} \cdot H_m - \sum_{n,m} \mathrm{CSPS}_{n,m} \cdot H_m \\
+ \quad & \mathrm{RPS\_Shortfall}
\end{aligned}
$$

State RPS Requirement: This allows the model to include state Renewable Portfolio Standards (RPS), wherein the total annual renewable generation must exceed a specified fraction of the state electricity load or a penalty must be paid on the shortfall.

$ST\_RPSConstraint_{states}$

$$
\begin{aligned}
St\_RPSfraction_{states} \cdot \sum_{n,m}^{n \in states} L_{n,m} \cdot H_m \quad \leq \quad & \sum_{c,i,j,m,l}^{j \in states} (\mathrm{WN}_{c,i,j,l} + \mathrm{WTN}_{c,i,j,l}) \cdot CF_{c,i,m,l} \cdot H_m \\
& \qquad \cdot (1 - TWLOSSnew \cdot Distance_{i,j})(1 - SurplusMar_{c,j}) \\
+ \quad & \sum_{c,i,j,m}^{j \in states} (WO_{c,i,j,l} + WTO_{c,i,j,l}) \cdot CF_{c,i,m,l} \cdot H_m \\
& \qquad \cdot (1 - TWLOSSold \cdot Distance_{i,j})(1 - SurplusOld_{c,j}) \\
+ \quad & \sum_{c,j,m}^{j \in states} \mathrm{Welec\_inregion}_{c,j,l} \cdot CF_{c,j,m,l} \cdot H_m \\
& \qquad \cdot (1 - SurplusMar_{c,j}) \\
+ \quad & \sum_{cCSP,i,j,m}^{j \in states} (\mathrm{CSPN}_{cCSP,i,j} + \mathrm{CSPTN}_{cCSP,i,j}) \cdot CF_{cCSP,m} \cdot H_m \\
& \qquad \cdot (1 - TWLOSSnew \cdot Distance_{i,j}) \\
+ \quad & \sum_{cCSP,i,j,m}^{j \in states} (CSPO_{cCSP,i,j} + CSPTO_{cCSP,i,j}) \cdot CF_{cCSP,m} \cdot H_m \\
& \qquad \cdot (1 - TWLOSSold \cdot Distance_{i,j}) \\
+ \quad & \sum_{cCSP,j,m}^{j \in states} \mathrm{CSPelec\_inregion}_{cCSP,j} \cdot CF_{cCSP,m} \cdot H_m \\
+ \quad & \sum_{c,i,m,st}^{j \in states} (\mathrm{WSTORin\_wind}_{c,i,m,st} + old\_WSTORin\_wind_{c,i,m,st}) \cdot H_m \\
+ \quad & \sum_{n,m}^{n \in states} (\mathrm{CONV}_{n,m,geothermal} + \mathrm{CONVP}_{n,m,geothermal}) \cdot H_m \\
+ \quad & \sum_{n,m}^{n \in states} (\mathrm{CONV}_{n,m,biopower} + \mathrm{CONVP}_{n,m,biopower}) \cdot H_m \\
+ \quad & \sum_{bioclass,n} \mathrm{CofireGen}_{bioclass,n} \\
- \quad & \sum_{n,m}^{n \in states} \mathrm{WS}_{n,m} \cdot H_m - \sum_{n,m}^{n \in states} \mathrm{CSPS}_{n,m} \cdot H_m \\
+ \quad & \mathrm{St\_RPS\_Shortfall}
\end{aligned}
$$

Limits on Existing Transmission: Due to extant transmission capacity usage and other limitations, the amount of wind power able to be transported on pre-2006 lines is limited. This constraint limits the wind imports on pre-2006 lines to some fraction of the capacity of the transmission lines crossing the boundaries of demand region j.

$WIND\_interregion\_trans_j$

$$\sum_{c,i,l} (\mathrm{WN}_{c,i,j,l} + WO_{c,i,j,l}) - \sum_{c,l} (\mathrm{WN}_{c,j,j,l} + WO_{c,j,j,l}) \quad + \sum_{cCSP,i} (\mathrm{CspN}_{cCSP,i,j} + CspO_{cCSP,i,j}) - \sum_{cCSP} (\mathrm{CspN}_{cCSP,j,j} + CspO_{cCSP,j,j}) \quad \leq \quad \sum_{k} a_k \cdot Tk_k$$

Regional Balancing Constraint: This constraint is a transmission capacity balance that defines the transmission capacity needed to handle wind and CSP transmission between balancing authorities. This transmission capacity required for wind/CSP is combined with that required by conventional generation to identify bottlenecks between balancing authorities. The left-hand side of the constraint is the sum of all wind and CSP generation transmitted into the balancing authority plus all that generated within. The right-hand side is the sum of all the wind and CSP generation consumed in- plus all that transmitted from the balancing authority.

$WIND\_BALANCE\_PCAS_n$

$$\begin{aligned} \sum_{p} \mathrm{ReT}_{n,p} \quad + & \\ \sum_{c,i,j,l}^{i \in n} (\mathrm{WN}_{c,i,j,l} + WO_{c,i,j,l}) \quad + & \\ \sum_{cCSP,i,j}^{i \in n} (\mathrm{CSPN}_{cCSP,i,j} + CspO_{cCSP,i,j}) \quad = & \quad \sum_{p} \mathrm{ReT}_{p,n} \\ & + \sum_{c,i,j,l}^{j \in n} (\mathrm{WN}_{c,i,j,l} + WO_{c,i,j,l}) \\ & + \sum_{cCSP,i,j}^{j \in n} (\mathrm{CSPN}_{cCSP,i,j} + CspO_{cCSP,i,j}) \end{aligned}$$

Conventional Transmission Constraint: Ensures that there is sufficient transmission capacity between contiguous balancing authorities n and p within the same grid interconnect to transmit wind generation and conventional generation in each time-slice m. Transmission capacity added this period is included in both directions p-to-n and n-to-p because transmission lines are bidirectional.[11]

$CONV\_TRAN\_PCA_{n,p,m}$

$$\mathrm{CONVT}_{n,p,m} + \mathrm{ReT}_{n,p} \quad \leq \quad \mathrm{TPCAN}_{n,p} + \mathrm{TPCAN}_{p,n} + TPCAO_{n,p}$$

[11]The $\mathrm{ReT}_{n,p}$ variable prevents ReEDS from shipping wind or CSP from supply region i to the closest demand region j; and, from there, continue to ship it as conventional power to other balancing authorities where generation is needed. The problem with this is that if new lines are required for this extended wind transmission to a different balancing authority, the wind will not have to pay for a dedicated transmission line, i.e. the transmission line cost will be spread over more hours than only those during which the wind blows.

Contracted Transmission Constraint: Ensures that there is sufficient transmission capacity between contiguous balancing authorities n and p within the same grid interconnect to transmit wind generation and contracted conventional capacity. Transmission capacity added this period is included in both directions p-to-n and n-to-p because transmission lines are bidirectional.

$CONTRACT\_TRAN\_PCA_{n,p}$

$$\mathrm{CONTRACTcap}_{n,p} + \mathrm{WT}_{n,p} + \mathrm{CspT}_{n,p} \quad \leq \quad \mathrm{TPCAN}_{n,p} + \mathrm{TPCAN}_{p,n} + TPCAO_{n,p}$$

Transmission Growth Constraints: These two constraints allocate new transmission capacity (MW) to bins that have costs associated with them over and above the cost of the transmission lines themselves. The bins are defined as a fraction of the national transmission capacity at the start of the period.

$TPCA\_GROWTH\_TOT$

$$\mathrm{TPCAN}_{n,p} + \sum_{c,i,j} \mathrm{WTN}_{c,i,j} + \sum_{cCSP,i,j} \mathrm{CspTN}_{cCSP,i,j} \quad \leq \quad \sum_{TPCA\_g} \mathrm{TPCA\_Ct}_{TPCA\_g}$$

$TPCA\_GROWTH\_BIN_{TPCA\_g}$

$$\mathrm{TPCA\_Ct}_{TPCA\_g} \quad \leq \quad TPCA\_Gt_{TPCA\_g} \cdot BASETPCA$$

A.4.4 Constraints on System Operation

Generation Requirement: This constraint ensures that the load (MW) in time period m in balancing authority n is met with power from conventional and renewable generators plus net imports from balancing authorities contiguous to n ($\mathrm{CONVT}_{n,p,m}$). Long-distance transmission from wind and CSP facilities and imports are decremented for transmission losses. Wind and CSP output are also decreased by wind curtailments. Storage can also contribute, but the charging of storage adds to the load requirement.
The *LOAD_PCA* constraint is the constraint that is affected by the mini-slices; for (n, m) pairs that qualify, it is split into three independent constraints (each with a different set of wind capacity factors) that must be dispatched separately.

LOAD_PCA$_{n,m}$

$$
\begin{aligned}
L_{n,m} \quad \leq \quad & \sum_{q} (\mathrm{CONVgen}_{n,m,q} + \mathrm{CONVP}_{n,m,q}) \\
+ \quad & \sum_{p} (\mathrm{CONVT}_{p,n,m} \cdot (1 - \mathit{TWLOSS} \cdot \mathit{Distance}_{n,p}) - \mathrm{CONVT}_{n,p,m}) \\
+ \quad & \sum_{c,i,j}^{j \in n} (\mathrm{WN}_{c,i,j,l} + \mathrm{WTN}_{c,i,j,l}) \cdot \mathit{CF}_{c,i,m,l} \cdot (1 - \mathit{SurplusMar}_{c,i,n}) \\
& \qquad \cdot (1 - \mathit{TWLOSSnew} \cdot \mathit{Distance}_{i,j}) \\
+ \quad & \sum_{c,j,l}^{j \in n} \mathrm{Welec\_inregion}_{c,j,l} \cdot \mathit{CF}_{c,j,m,l} \cdot (1 - \mathit{SurplusMar}_{c,i,n}) \\
+ \quad & \sum_{c,i,j,l}^{j \in n} (\mathit{WO}_{c,i,j,l} + \mathit{WTO}_{c,i,j,l}) \cdot \mathit{CFO}_{c,i,m,l} \cdot (1 - \mathit{SurplusOld}_{c,i,n}) \\
& \qquad \cdot (1 - \mathit{TWLOSSold} \cdot \mathit{Distance}_{i,j}) \\
- \quad & \mathrm{WS}_{n,m} \\
+ \quad & \sum_{cCSP,i,j}^{j \in n} (\mathrm{CSPN}_{cCSP,i,j} + \mathrm{CSPTN}_{cCSP,i,j}) \cdot \mathit{CF}_{cCSP,m} \cdot (1 - \mathit{TWLOSSnew} \cdot \mathit{Distance}_{i,j}) \\
+ \quad & \sum_{cCSP,j}^{j \in n} \mathrm{CSPelec\_inregion}_{cCSP,j} \cdot \mathit{CF}_{cCSP,m} \\
+ \quad & \sum_{cCSP,i,j}^{j \in n} (\mathit{CSPO}_{cCSP,i,j} + \mathit{CSPTO}_{cCSP,i,j}) \cdot \mathit{CF}_{cCSP,m} \cdot (1 - \mathit{TWLOSSold} \cdot \mathit{Distance}_{i,j}) \\
- \quad & \mathrm{CSPS}_{n,m} \\
+ \quad & \sum_{st} (\mathrm{STORout}_{n,m,st} - \mathrm{STORin}_{n,m,st}) \\
+ \quad & \sum_{i,st} (\mathrm{WSTORout\_dest}_{i,n,m} + \mathit{old\_WSTORout\_dest}_{i,n,m}) \\
& \qquad \cdot (1 - \mathit{TWLOSSnew} \cdot \mathit{Distance}_{i,n}) \\
+ \quad & \sum_{i,st}^{i \in n} \mathrm{WSTORout\_inregion}_{i,m,st} + \mathit{old\_WSTORout\_inregion}_{i,m,st} \\
- \quad & \sum_{j,st}^{j \in n} \mathrm{WSTORin\_grid}_{j,m,st} + \mathit{old\_WSTORin\_grid}_{j,m,st}
\end{aligned}
$$

Reserve Margin Requirement: Ensures that the conventional and storage capacity (MW) and capacity value of wind and CSP during the peak summer period is large enough to meet the peak load plus a reserve margin and any storage input requirements. Peak-load requirements in NERC region *r* can also be met by contracting for capacity located in other NERC regions.

RES_MARG_{rto}

$$
\begin{aligned}
\sum_{n}^{n \in rto} P_{rto} \cdot (1 + RM_{rto}) \quad \leq \quad & \sum_{n,q}^{n \in rto} \mathrm{CONV}_{n,q} \\
+ \quad & \sum_{c,i,j}^{j \in rto} (\mathrm{WN}_{c,i,j} + \mathrm{WTN}_{c,i,j}) \cdot CVmar_{c,i,rto} \\
& \qquad \cdot (1 - TWLOSSnew \cdot Distance_{i,n}) \\
+ \quad & \sum_{c,i,j}^{j \in rto} (WO_{c,i,j} + WTO_{c,i,j}) \cdot CVold_{c,i,rto} \\
& \qquad \cdot (1 - TWLOSSold \cdot Distance_{i,n}) \\
+ \quad & \sum_{c,j,escp}^{j \in rto} \mathrm{Welec\_inregion}_{c,j,escp} \cdot CVmar_{c,i,rto} \\
+ \quad & \sum_{cCSP,i,j}^{j \in rto} (\mathrm{CspN}_{cCSP,i,j} + \mathrm{CspTN}_{cCSP,i,j}) \cdot CspCVmar_{cCSP,i,rto} \\
& \qquad \cdot (1 - TWLOSSnew \cdot Distance_{i,n}) \\
+ \quad & \sum_{cCSP,i,j}^{j \in rto} (CspO_{cCSP,i,j} + CspTO_{cCSP,i,j}) \cdot CspCVold_{cCSP,i,rto} \\
& \qquad \cdot (1 - TWLOSSold \cdot Distance_{i,n}) \\
+ \quad & \sum_{cCSP,j,escp}^{j \in rto} \mathrm{CSPelec\_inregion}_{cCSP,j,escp} \cdot CspCVmar_{cCSP,i,rto} \\
+ \quad & \sum_{n,st}^{n \in rto} \mathrm{STOR}_{n,st} + old\_STOR_{n,st} \\
+ \quad & \sum_{n}^{i \in rto} \mathrm{WSTORout\_dest}_{i,n,H16} + old\_WSTORout\_dest_{i,n,H16} \\
& \qquad \cdot (1 - TWLOSSold \cdot Distance_{i,n}) \\
+ \quad & \sum_{i,st}^{i \in n} \mathrm{WSTORout\_inregion}_{i,H16,st} + old\_WSTORout\_inregion_{i,H16,st} \\
+ \quad & \sum_{n,p}^{n \in rto} \mathrm{CONTRACTcap}_{p,n} \cdot (1 - TLOSS \cdot Distance_{n,p}) \\
- \quad & \sum_{n,p}^{n \in rto} \mathrm{CONTRACTcap}_{n,p}
\end{aligned}
$$

Operating Reserve Requirement: Ensures that the spinning reserve, quick-start capacity, and storage capacity are adequate to meet the normal operating reserve requirement and that imposed by wind. The second and third constraints work together to ensure that no more than a set fraction (*qsfrac*) of the operating reserve requirement be met by quickstart capacity.

$OPER\_RES_{rto,m}$

$$\begin{aligned} Oper\_Res\_Reqt_{rto,m} \quad \leq \quad & \sum_{n,q}^{n\in rto} \mathrm{SR}_{n,m,q} + \mathrm{QS}_{n,q} \cdot F_q \\ + \quad & \sum_{n,st}^{n\in rto} \mathrm{STOR\_OR}_{n,m,st} + \sum_{i,st}^{i\in rto} \mathrm{WSTOR\_OR}_{i,m,st} + old\_WSTOR\_OR_{i,m,st} \end{aligned}$$

$OPER\_RES2_{m,rto}$

$$\begin{aligned} Oper\_Res\_Reqt_{rto,m} \quad = \quad & TOR_{rto,m} \\ & + \sum_{c,i,j}^{j\in rto} (\mathrm{WN}_{i,j} + \mathrm{WTN}_{i,j}) \cdot ORmar_{c,i,rto,m} \\ & + \sum_{c,j}^{j\in rto} \mathrm{Welec\_inregion}_{c,j} \cdot ORmar_{c,j,rto}) \end{aligned}$$

$OPER\_RES3_{rto,m}$

$$\sum_{n,q}^{n\in rto} \mathrm{QS}_{n,q} \cdot F_q \quad \leq \quad qsfrac \cdot Oper\_Res\_Reqt_{rto,m}$$

Spinning Reserve Constraint: Ensures that the useful generation from a conventional plant of type q comprises at least a minimum fraction of the total generation in time-slice m in balancing authority n.

$SPIN\_RES\_CAP_{n,m,q}$

$$\mathrm{SR}_{n,m,q} \quad \leq \quad \mathrm{CONVgen}_{n,seasonpeak,q} \cdot FSRV_q$$

Capacity Dispatch Constraint: Ensures that the capacity (MW) in balancing authority n of type q—derated by the average forced outage rate for type q generators—is adequate to meet the load, quick-start, and spinning reserve required in time-slice m.

$CAP\_FO\_PO_{n,m,q}$

$$\mathrm{CONVgen}_{n,m,q} + \mathrm{SR}_{n,m,q} + \mathrm{QS}_{n,q} \quad \leq \quad \mathrm{CONV}_{n,q} \cdot (1 - FO_q)(1 - PO_{m,q})$$

Peaking Constraint: To prevent unrealistic cycling, base-load plants are constrained in peak time-slices to generate no more electricity than the average of that which is generated in the shoulder time-slices. Additional power is available through *CONVP*, at increased cost.

$B\_peak\_12_{n,m,q}$

$$
\begin{aligned}
\text{CONVgen}_{n,H3,q\in baseload} &\leq (\text{CONVgen}_{n,H2,q\in baseload} + \text{CONVgen}_{n,H4,q\in baseload})/2 \\
\text{CONVgen}_{n,H7,q\in baseload} &\leq (\text{CONVgen}_{n,H6,q\in baseload} + \text{CONVgen}_{n,H8,q\in baseload})/2 \\
\text{CONVgen}_{n,H12,q\in baseload} &\leq (\text{CONVgen}_{n,H10,q\in baseload} + \text{CONVgen}_{n,H11,q\in baseload})/2 \\
\text{CONVgen}_{n,H15,q\in baseload} &\leq \text{CONVgen}_{n,H14,q\in baseload} \\
\text{CONVgen}_{n,H16,q\in baseload} &\leq (\text{CONVgen}_{n,H2,q\in baseload} + \text{CONVgen}_{n,H4,q\in baseload})/2
\end{aligned}
$$

Minimum Load Constraint: To prevent baseload plants from ramping down to unrealistic levels, minimum power output can not fall below a set fraction of peak power output.

$MIN\_LOADING_{n,m,q}$

$$
\text{CONVgen}_{n,m,q} + \text{CONVP}_{n,m,q} \geq \text{CONVgen}_{n,seasonpeak,q} \cdot minplantload_q
$$

A.4.5 Constraints on Storage

Storage Charging Constraint, Wind: Generation from wind turbines can either go onto the grid immediately or directly into wind-sited storage.

$WIND\_2\_STORAGE_{c,i,m}$

$$
\begin{aligned}
&\sum_j (\text{WN}_{c,i,j} + \text{WTN}_{c,i,j}) \cdot CF_{c,i,m} \quad + \\
&WELEC\_inregion_{c,i} \cdot CF_{c,i,m} \quad + \\
&\sum_{st} \text{WSTORin\_wind}_{c,i,m,st} \leq (\text{WturN}_{c,i} + \text{WturTN}_{c,i} + \text{Wtur\_inregion}_{c,i}) \cdot CF_{c,i,m}
\end{aligned}
$$

Storage Charging Constraint, Grid: There must be sufficient transmission capacity to wind farms in region i to accept any energy being used to charge wind-sited storage in that region.

$GRID\_2\_STORAGE_{i,m}$

$$
\sum_{st} \text{WSTORin\_grid}_{i,m,st} \leq \sum_{c,j} (\text{WN}_{c,i,j} + \text{WTN}_{c,i,j}) + \sum_c \text{WELEC\_inregion}_{c,i}
$$

Storage Charging Constraint, Competition: Wind-energy gets precedence over grid-energy for charging storage.

$GRID\_LIMIT_{i,s}$

$$
\sum_{m,st}^{m\in s} WSTORin\_grid_{i,m,st} \leq \sum_{c,m,st}^{m\in s} WSTORin\_wind_{c,i,m,st} \cdot \frac{1 - CF_{c,i,s}}{CF_{c,i,s}}
$$

Storage Power Constraint: Transmission lines for wind may downsize compared to the capacity of the wind farm if there is storage at the site. Storage power must compensate for any shortfall, i.e. all wind power must be able to go into either the grid or storage.

STORAGE_INPUT_CAPACITY$_i$

$$\begin{aligned}\sum_{st} \mathrm{WSTOR}_{i,st} \quad &\geq \quad \sum_{c} (\mathrm{WturN}_{c,i} + \mathrm{WturTN}_{c,i} + \mathrm{Wtur\_inregion}_{c,i}) \\ &- \quad \sum_{c,j} (\mathrm{WN}_{c,i,j} + \mathrm{WTN}_{c,i,j} + \mathrm{WELEC\_inregion}_{c,i})\end{aligned}$$

Storage Power Constraint: Power discharged from storage during the peak period of each season may not exceed the expected amount of available transmission once wind has taken its share.

STORAGE_PEAK_OUT$_{i,p,s}$

$$\mathrm{WSTORout\_dest}_{i,p,seasonpeak} \quad \leq \quad \sum_{c,j}^{j\in p} (\mathrm{WN}_{c,i,j} + \mathrm{WTN}_{c,i,j}) \cdot (1 - CF_{c,i,s})$$

STORAGE_PEAK_IN$_{p,s}$

$$\mathrm{WSTORout\_dest}_{i,p,seasonpeak} \quad \leq \quad \sum_{c,i,j}^{j\in p} (\mathrm{WN}_{c,i,j} + \mathrm{WTN}_{c,i,j}) \cdot (1 - CF_{c,i,s})$$

STORAGE_PEAK_INREGION$_{i,s}$

$$\mathrm{WSTORout\_inregion}_{i,seasonpeak,st} \quad \leq \quad \sum_{c} \mathrm{WELEC\_inregion}_{c,i} \cdot (1 - CF_{c,i,seasonpeak})$$

Storage Discharge Constraint: To reduce the overall variable count, the variable governing energy discharged from storage, $\mathrm{WSTORout}_{i,p,m,st}$, was broken down into two, $\mathrm{WSTORout\_dest}_{i,m,p}$ and $\mathrm{WSTORout\_source}_{i,m,st}$. This constraint ties those two variables together.

STORAGE_SOURCE_MATCH$_{i,m}$

$$\sum_{p} \mathrm{WSTORout\_dest}_{i,p,m} \quad = \quad \sum_{st} \mathrm{WSTORout\_source}_{i,m,st}$$

Energy Balance: Energy discharged from storage type st in each area i or n must not exceed the energy used to charge storage—multiplied by the round-trip efficiency for type st generators—within a single season.

ENERGY_FROM_GRID_STORAGE$_{n,s,st}$

$$\sum_{m}^{m\in s} \mathrm{STORout}_{n,m,st} \cdot H_m \quad \leq \quad \sum_{m}^{m\in s} \mathrm{STORin}_{n,m,st} \cdot H_m \cdot STOR\_RTE_{st}$$

ENERGY_FROM_WIND_STORAGE$_{i,s,st}$

$$\sum_{m}^{m \in s} \Big(\text{WSTORout\_source}_{i,m,st} + \text{WSTORout\_inregion}_{i,m,st} \Big) \cdot H_m \quad \leq \quad \sum_{m}^{m \in s} \Big(\sum_{c} \text{WSTORin\_wind}_{c,i,m,st} + \text{WSTORin\_grid}_{i,m,st} \Big) H_m \cdot STOR\_RTE_{st}$$

Storage Dispatch Constraint: Ensures that storage capacity of type *st*—derated by the average forced outage rate for type *st* generators—is adequate to supply all charging power, discharging power, and operating reserve demanded in each time-slice *m*.

STORE_FO_PO_GRID$_{n,m,st}$

$$\text{STORout}_{n,m,st} + \text{STORin}_{n,m,st} + \text{STOR\_OR}_{n,m,st} \quad \leq \quad (\text{STOR}_{n,st} + old\_STOR_{n,st})(1 - FO_{st})(1 - PO_{m,st})$$

STORE_FO_PO_WIND$_{i,m,st}$

$$\begin{aligned} \text{WSTORin\_wind}_{i,m,st} + \text{WSTORin\_grid}_{i,m,st} \quad & + \\ \text{WSTORout\_source}_{i,m,st} + \text{WSTORout\_inregion}_{i,m,st} \quad & + \\ \text{WSTOR\_OR}_{i,m,st} \quad & \leq \quad \text{WSTOR}_{i,st}(1 - FO_{st})(1 - PO_{m,st}) \end{aligned}$$

Storage Growth Constraint: These two constraints allocate new storage capacity (MW) to bins that have costs associated with them over and above the cost of the storage capacity itelf. The bins are defined as a fraction of the national storage capacity at the start of the period.

STORAGE_GROWTH_TOT$_{st}$

$$\sum_{i} \text{WSTOR}_{i,st} + \sum_{n} \text{STOR}_{n,st} \quad \leq \quad \sum_{storagebp} \text{STORAGEBIN}_{st,storagebp}$$

STORAGE_GROWTH_BIN$_{st,storagebp}$

$$\text{STORAGEBIN}_{st,storagebp} \quad \leq \quad STORAGEBINCAP_{st,storagebpt} \cdot BASE\_STORAGE_{st};$$

A.4.6 Others

Hydropower Energy Constraint: Restricts the energy available from hydroelectric capacity to conform to the historical availability of water.

HYDRO_ENERGY$_n$

$$\sum_{m} \text{CONVgen}_{n,m,hydro} \quad \leq \quad Hen_n$$

California Coal Restriction: Western states can generate no more energy from coal or ogs (plants that are dirtier than gas-cc) than they can consume in-state. This is to prevent them from shipping coal-generated electricity to California.

CALIFORNIA_COAL$_{WECCstates,m}$

$$\sum_{dirty,n}^{n\in states} \left(\mathrm{CONVgen}_{n,m,dirty} + \mathrm{CONVP}_{n,m,dirty}\right) \quad \leq \quad \sum_{n}^{n\in states} L_{n,m}$$

Generation from Low Sulfur Coal: This constraint essentially adds all the coal used in the different time slices throughout the year into a single variable.

LOWSULCOAL$_{n,q}$

$$\mathrm{coallowsul}_{n,q\in coaltech} \quad \leq \quad \sum_{m}(\mathrm{CONVgen}_{n,m,q} + \mathrm{CONVP}_{n,m,q}) \cdot H_m$$

SO_2 Scrubbers Constraint: Combined capacity of the scrubbed and unscrubbed coal plants must be equal to the total of the two from the last period minus retirements. Furthermore, unscrubbed coal capacity can not exceed the unscrubbed capacity of the last period minus retirements. This allows the unscrubbed to become scrubbed, i.e., the unscrubbed capacity can decrease but the total can not. Scrubbed coal plants can be converted to cofiring via the same mechanism,

SCRUBBER$_n$

$$\begin{aligned} \mathrm{CONV}_{n,scr} + \mathrm{CONV}_{n,uns} + \mathrm{CONV}_{n,cofire} \quad &= \quad CONVold_{n,scr} - CONVret_{n,scr} \\ &+ \quad CONVold_{n,uns} - CONVret_{n,uns} \\ &+ \quad CONVold_{n,cofire} \end{aligned}$$

-and-

$$\mathrm{CONV}_{n,uns} \quad \leq \quad CONVold_{n,uns} - CONVret_{n,uns}$$

COFIRE_CAPACITY$_n$

$$\mathrm{CONV}_{n,scr} + \mathrm{CONV}_{n,cofire} \quad \geq \quad CONVold_{n,src} - CONVret_{n,scr} + CONVold_{n,cofire}$$

Emissions Constraint: Ensures that the national annual emission of each pollutant (CO_2, SO_2, NO_x, Hg) by all generators is lower than a national cap.

EMISSIONS$_{pol}$

$$\begin{aligned} \mathrm{LP}_{pol} \quad \geq \quad & \sum_{n,m,q}(\mathrm{CONVgen}_{n,m,q} + \mathrm{CONVP}_{n,m,q}) \cdot H_m \cdot CONVpol_{q,pol} \cdot CHeatrate_q \\ + \quad & \sum_{n,m} \mathrm{STORout}_{n,m,st} \cdot STORpol_{st,pol} \cdot CHeatrate_{st} \\ - \quad & \sum_{q,n,pol}^{pol=SO_2} \mathrm{coallowsul}_{n,q} \cdot CONVpol_{q,pol} \cdot CHeatrate_q \cdot coallowsulpolred \\ - \quad & \sum_{bioclass,n} \mathrm{CofireGen}_{bioclass,n} \cdot CHeatrate_{cofire} \cdot (CONVpol_{coal,pol} - CONVpol_{biomass,pol}) \end{aligned}$$

Geothermal Constraints: These constraints regulate the expansion of geothermal capacity. Regional capacity is constrained by a recoverable capacity supply curve. Geothermal capacity, as shown below, is linked directly to $\mathrm{CONV}_{q,n}$ and, through it, the model's framework for dispatchable conventional technologies.

GEOTHERMAL_GROWTH$_n$

$$\begin{aligned}\mathrm{CONV}_{n,geothermal} - CONVold_{n,geothermal} &= \sum_{geoclass} \mathrm{GeoBin}_{geoclass,n} \\ &+ \sum_{egsclass} \mathrm{GeoEGSbin}_{egsclass,n}\end{aligned}$$

GEOTHERMAL_GROWTH_BIN$_{geoclass,n}$

$$\mathrm{GeoBin}_{geoclass,n} + GeoOld_{geoclass,n} \leq GeoMax_{geoclass,n}$$

GEOEGS_GROWTH_BIN$_{egsclass,n}$

$$\mathrm{GeoEGSbin}_{egsclass,n} + GeoEGSOld_{egsclass,n} \leq GeoEGSmax_{egsclass,n}$$

Biofuel Constraints: These constraints regulate the capacity expansion of dedicated biomass and coal-biomass cofiring plants. Total bio-fired generation is limited by a regional feedstock supply curve. In cofired plants, biomass can contribute up to 15% of the feedstock. Biomass, like geothermal, is linked directly to the conventional variables such as $\mathrm{CONV}_{n,q}$ and $\mathrm{CONVgen}_{n,m,q}$.

BIOPOWER_GROWTH$_n$

$$\mathrm{CONV}_{n,biopower} - CONVold_{n,biopower} = \sum_{bioclass} \mathrm{BioBin}_{bioclass,n}$$

COFIRE_GENERATION$_n$

$$\sum_{bioclass} \mathrm{CofireGen}_{bioclass,n} \leq 0.15 \cdot \sum_{q,m} \mathrm{CONVgen}_{n,m,cofire}$$

BIOPOWER_GENERATION$_{bioclass,n}$

$$\begin{aligned}&\mathrm{BioGeneration}_{bioclass,n} \cdot CHeatrate_{biopower} + \\ &\quad \mathrm{CofireGen}_{bioclass,n} \cdot CHeatrate_{cofire} \leq BioSupply_{bioclass,n}\end{aligned}$$